



# **Receptivity of Hypersonic Boundary Layers to Acoustic Disturbances**

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**NATO STO AVT-240 & RTG-082:  
Hypersonic Boundary-Layer Transition Prediction  
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# Objectives

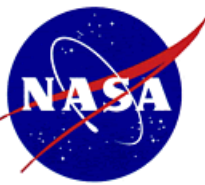
- The physics based  $e^N$  correlation method ( emalik<sup>3D</sup>, LASTRAC, STABLE etc. ) is easy to implement and yields satisfactory results if appropriate N-Factors are used to fix the transition onset. This factor depends on several parameters including geometry, tunnel noise and surface roughness. However, the N-Factors vary broadly and it becomes difficult to predict the onset accurately.
- Can we improve it? How can we achieve this?
- We have
  - **To include the effects of freestream disturbances on the transition process in the transition prediction methods**
  - **To identify a criterion to determine the transition onset point**



# Results

- Show the results for
  - **Flow over a 7-deg cone at Mach 10. Experiments were performed recently in the T9 Tunnel.**
  - **Flow over a sharp and a blunt flared-cones at Mach 6. Experiments were performed in the Purdue Tunnel.**
  - **HIFiRE-1 Flight Experiment.**

# Flow over a Cone at M=10 (Expts. Performed at T9, Marineau et al. AIAA 2014-3108)



## Parameters

Case	$R_n$ (mm)	$P_o$ (MPa)	$T_o$ (K)	$M_\infty$	$p_\infty$ (kPa)	$T_\infty$ (K)	Re/m (1E6/m)
1 (3745)	0.152	2.3	982	9.39	82.34	52.69	2.03
2 (3743)	0.152	8.9	1018	9.60	275.15	52.38	7.03
3 (3742)	0.152	22.6	1035	9.86	584.97	50.62	16.25

Cone half-angle = 7 deg.

$$T_{\text{wall}} = 0.3 * T_o$$

$$\text{Pr} = 0.74$$

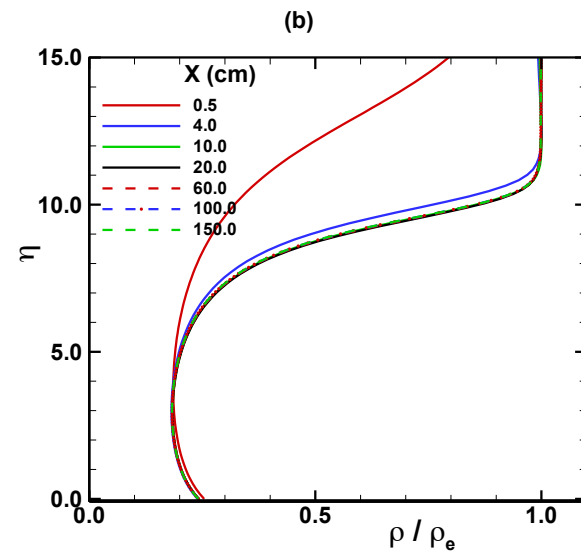
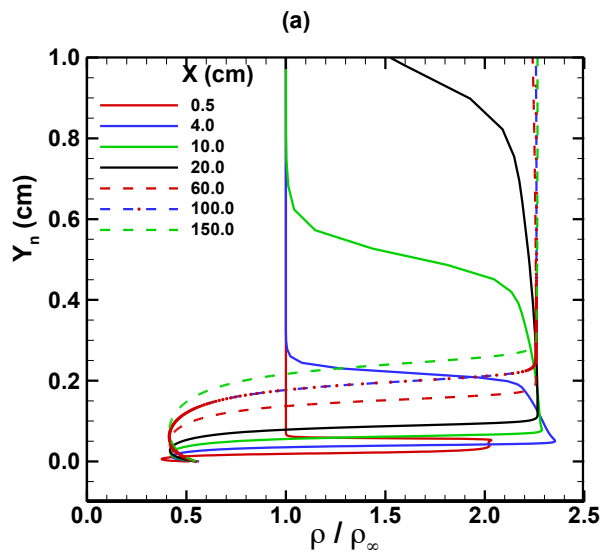
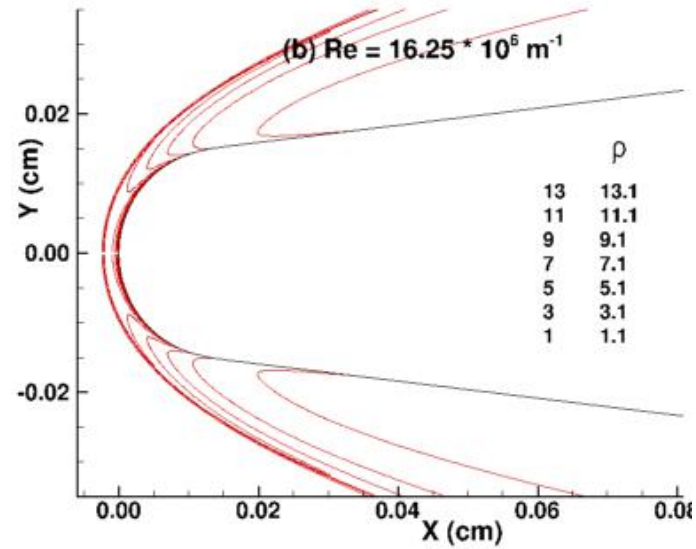
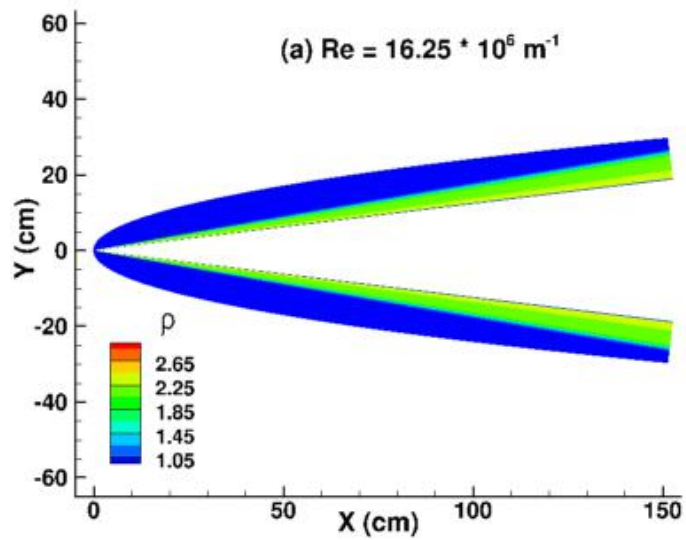
$$\gamma = 1.4$$

Gas constant  $R = 297$ .

Sutherland viscosity law =  $1.458 * 10^{-6} T^{1.5} / (T + 102.7 \text{ K})$

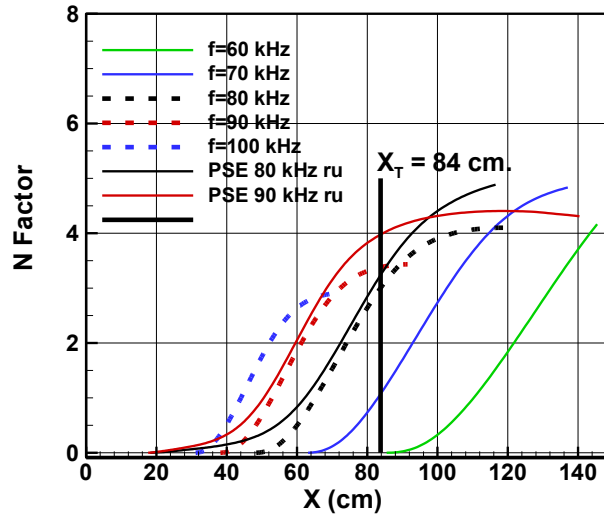
Leading edge of the cone: Sphere with radius,  $R_n$

# Mean Flow (Case 3)

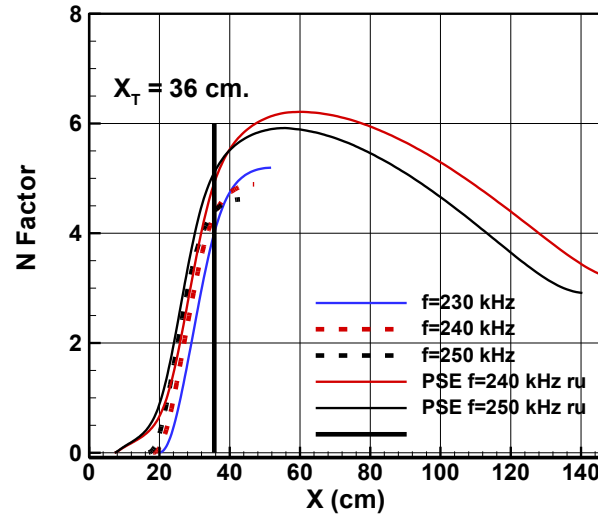


# N-Factors (Cases 1-3)

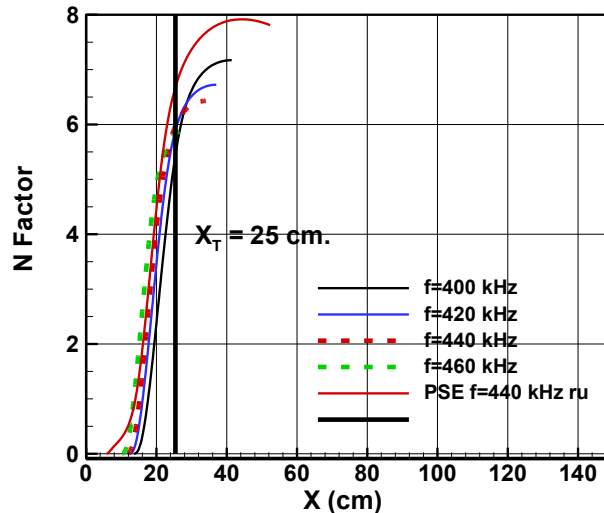
(a) Case 1



(b) Case 2



(c) Case 3

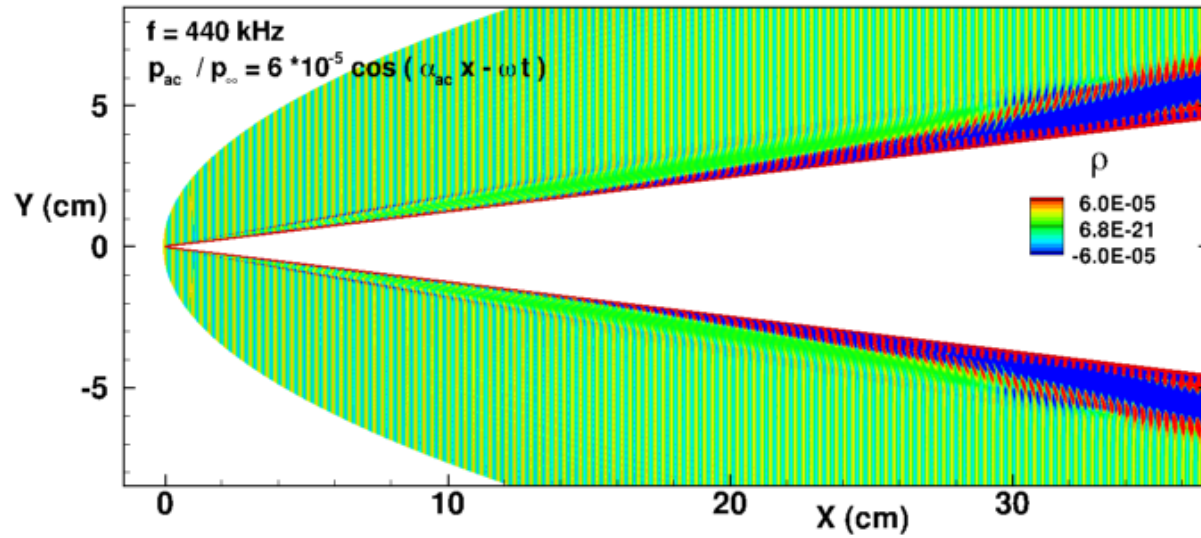


## Transition Parameters

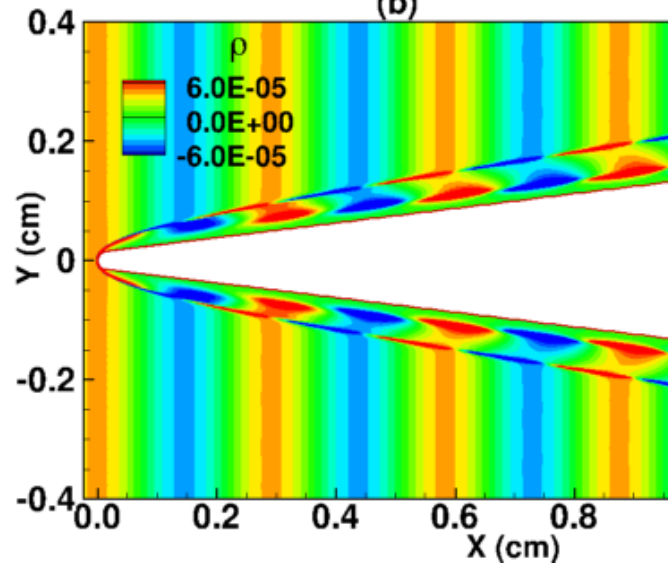
Case	$R_n$ (mm)	$Re/m$ (1E6/m)	$S_T$ (m)	N	f (kHz)
1 (3745)	0.152	2.03	0.84	4.1	90
2 (3743)	0.152	7.03	0.36	5.1	240
3 (3742)	0.152	16.25	0.25	7.0	440

# DNS

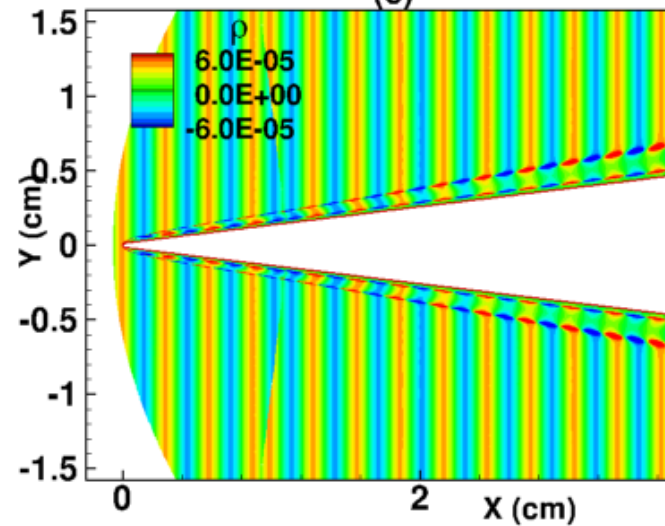
(a)



(b)

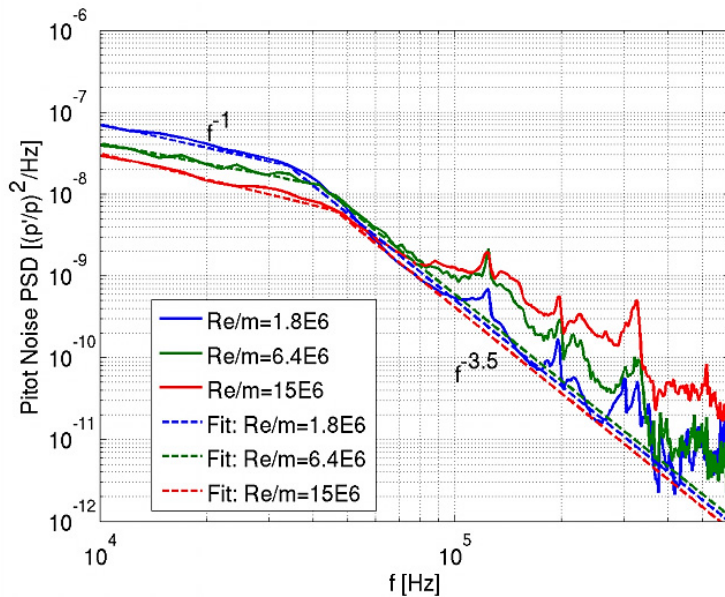
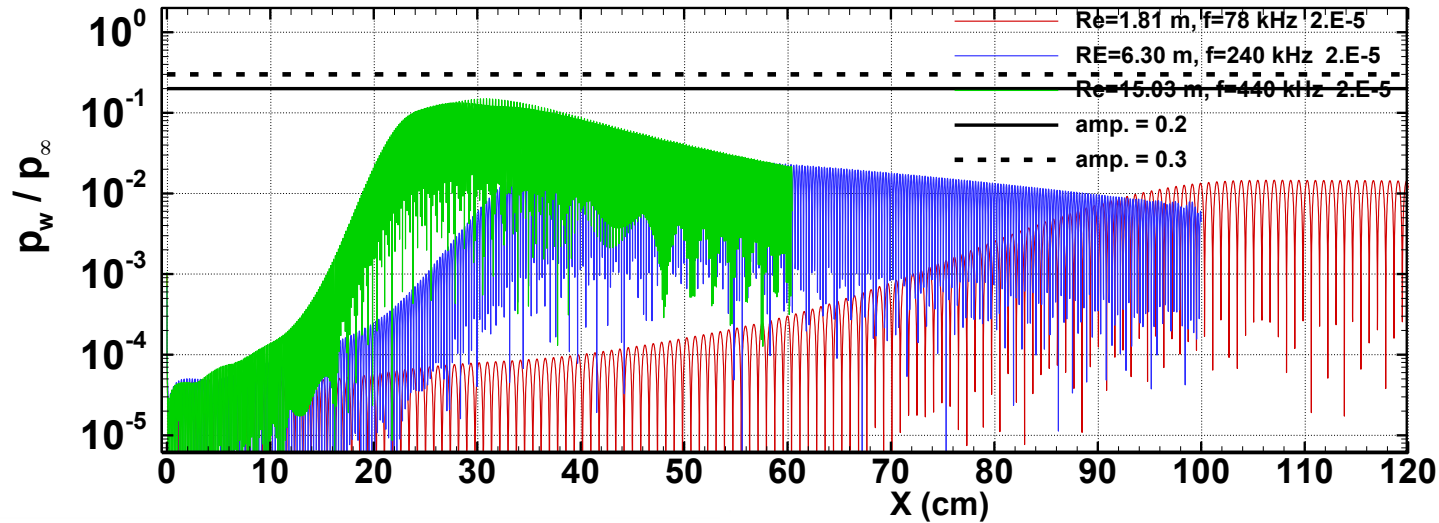


(c)



# DNS

Cases 1-3



$$p_{ac}(x, t) = \tilde{p}_{ac} e^{i(\alpha_{ac}x - \omega t)} + c.c.,$$

$$(p_{ac})_{PSD} = 2 \left( \tilde{p}_{ac} \right)^2$$

$$\text{Measured spectrum} \quad (p_{ac})_{PSD} = C \quad f^{-3.5} / \text{Hz}$$

$$2 \left( \tilde{p}_{ac} \right)^2 = C \quad f^{-3.5} \Delta f$$

$$\Delta f \sim 10 \text{ to } 100 \text{ kHz} \quad (\text{need to investigate more})$$

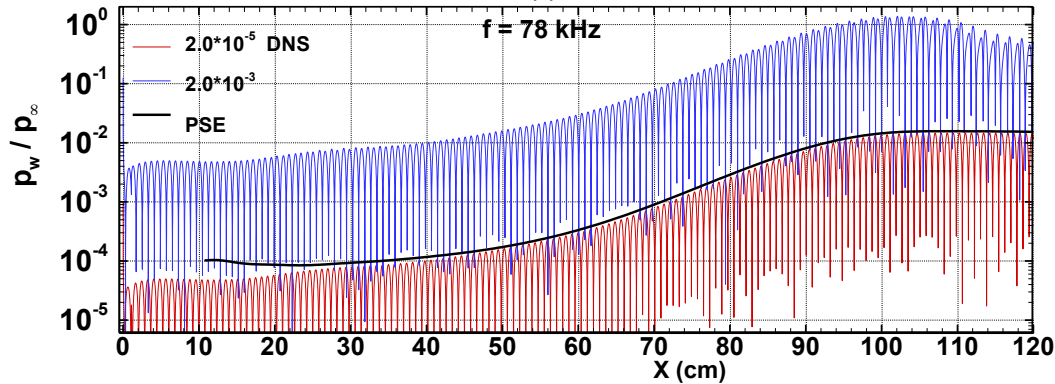
Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)





# DNS

(a) Case 1

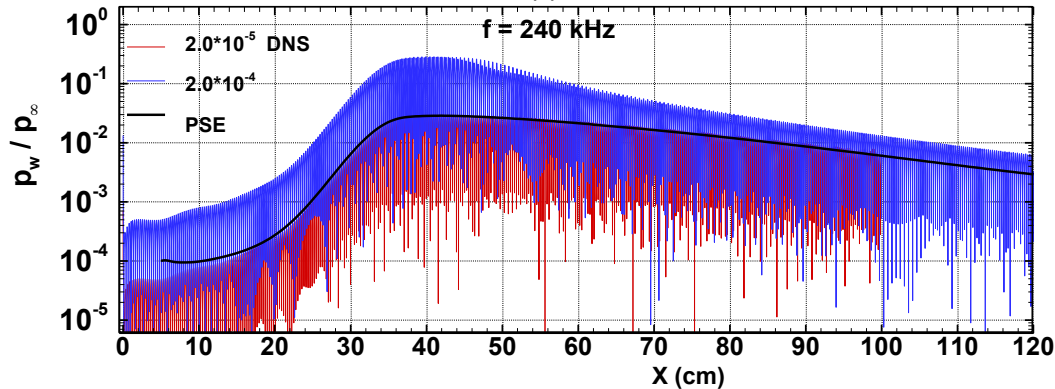


$$C_{recpt, p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$

$$= 2.0 \quad (x \sim 0)$$

$$= 4.5 \quad (x \sim 23 \text{ cm})$$

(b) Case 2

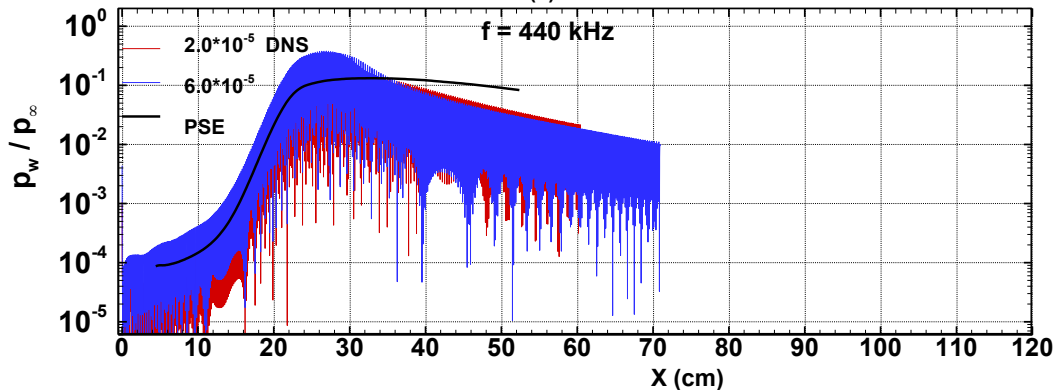


$$C_{recpt, p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$

$$= 2.0 \quad (x \sim 0)$$

$$= 5.0 \quad (x \sim 9 \text{ cm})$$

(c) Case 3



$$C_{recpt, p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$

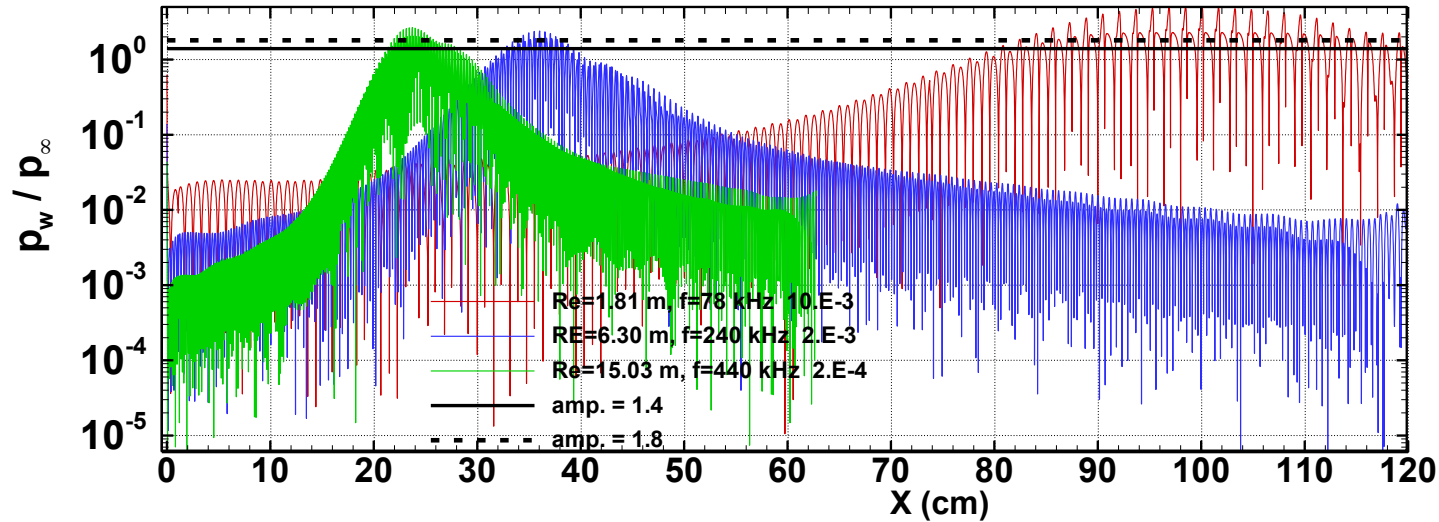
$$= 2.0 \quad (x \sim 0)$$

$$= 5.0 \quad (x \sim 5 \text{ cm})$$



# DNS

Cases 1-3



$$\frac{p_s}{p_\infty} = 3.29$$

## Transition Onset

Case	$X_T$ (cm)			N		
	$(p_{amp})_T$		Expt.	$(p_{amp})_T$		PSE
	1.4	1.8		1.4	1.8	
1	81	84	84	3.2	3.6	4.1
2	33	34	36	5.3	5.7	5.1
3	22	23	25	6.5	6.9	7.0

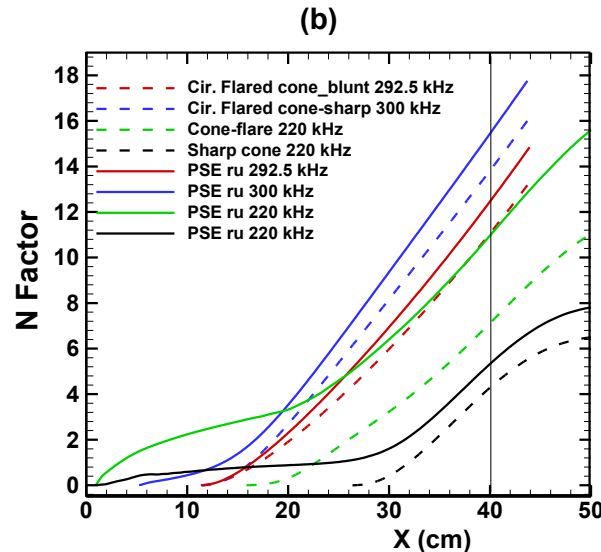
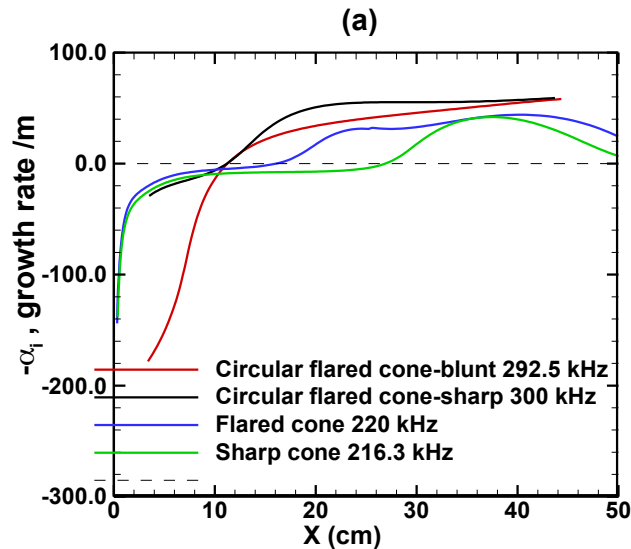
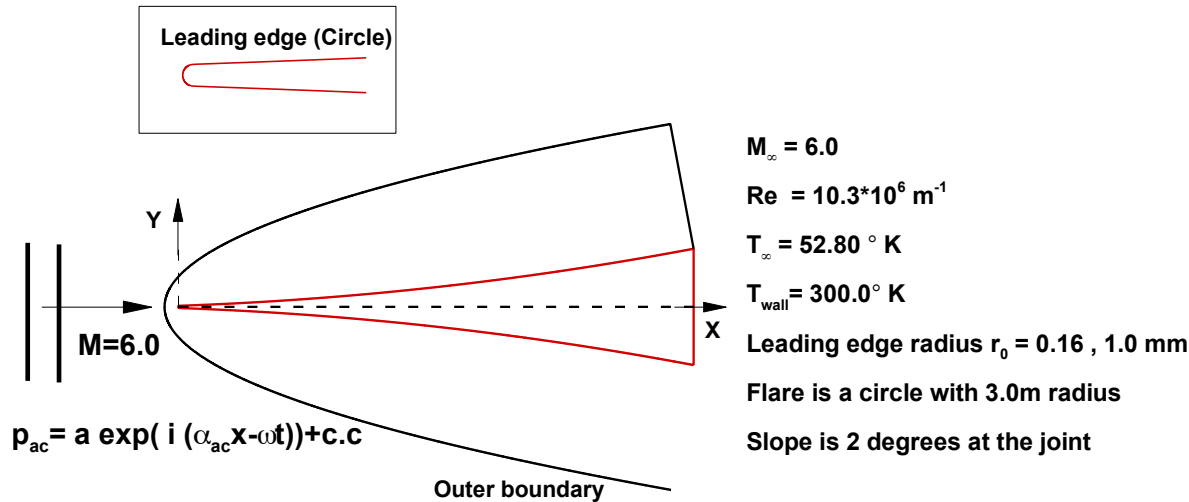
$$N_T = \frac{(p_{amp})_T}{C_{recpt, p_{wall}} p_{ac}}$$



## **Conclusions**

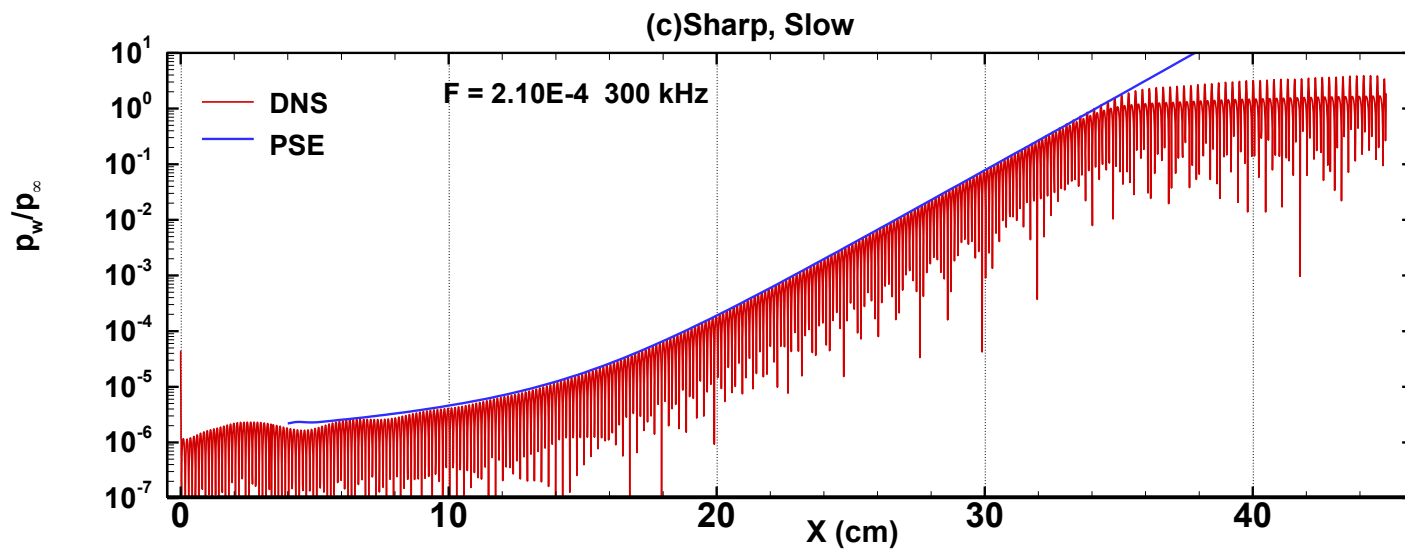
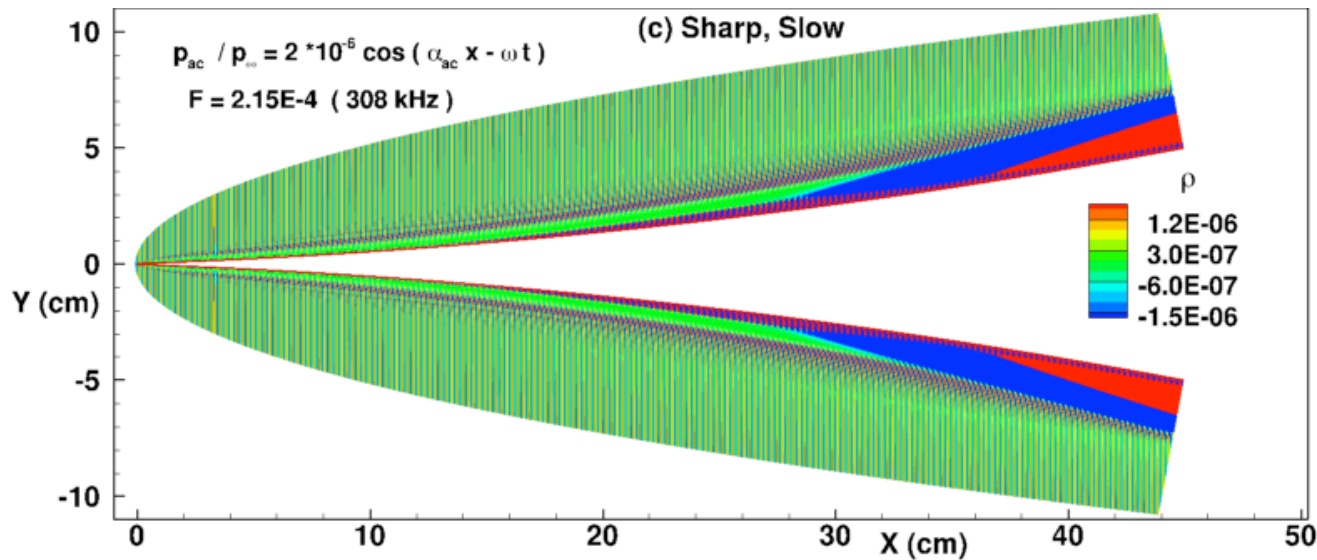
- Transition onset points are predicted using the receptivity and a criteria based on the surface pressure.
- The criteria on the pressure has to be validated for other cases.
- The bandwidth for the amplitude calculations also has to be verified.
- Whether single frequency with equivalent amplitude or the multiple frequencies with small amplitudes is the right approach?

# Mean Flow and Stability (Purdue Flared-Cones)



**X = 40 cm**  
**N=15 (sharp), 292 kHz**  
**N=13 (Blunt), 300 kHz**

# DNS (Flared-Sharp-Cone)



$$C_{recpt, p_{wall}} = \frac{(p_{wall})_n}{p_{ac}} = 1.0 \quad (x \sim 0)$$

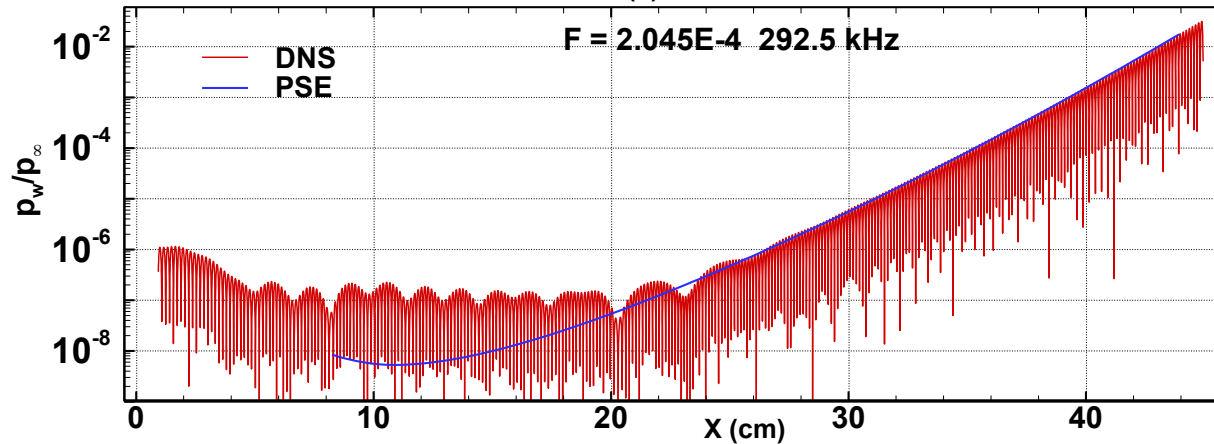
$$\frac{p_{wall}}{p_{\infty}} = 0.4 \quad (x \sim 33cm)$$

$$= 1.0 \quad (x \sim 36cm)$$



# DNS (Flared-Blunt-Cone)

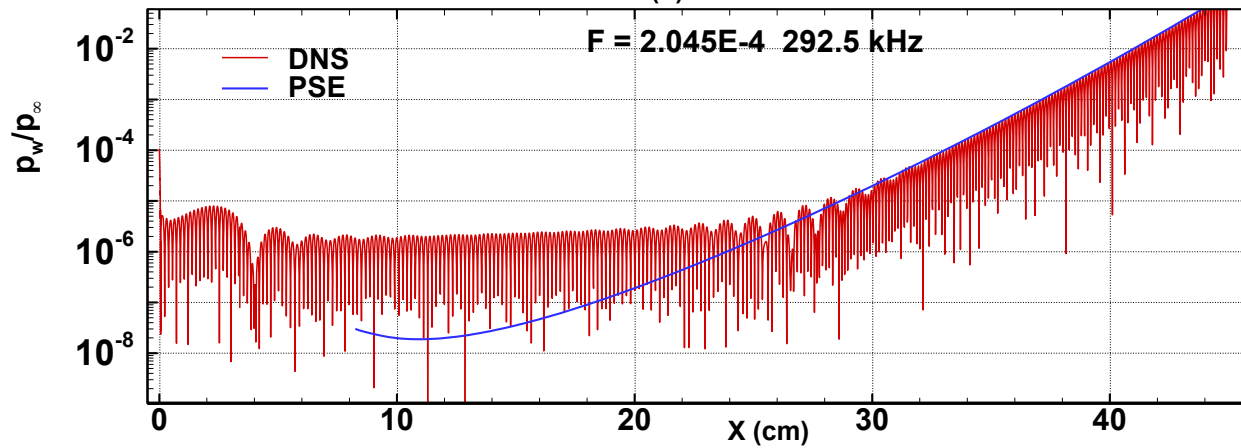
(a) Slow



$$C_{recpt, p_{wall}} = \frac{(p_{wall})_n}{p_{ac}} = 5 * 10^{-3} \quad (x \sim 10cm)$$

$$\frac{p_{wall}}{p_\infty} = 0.0028 \quad (x \sim 40cm)$$

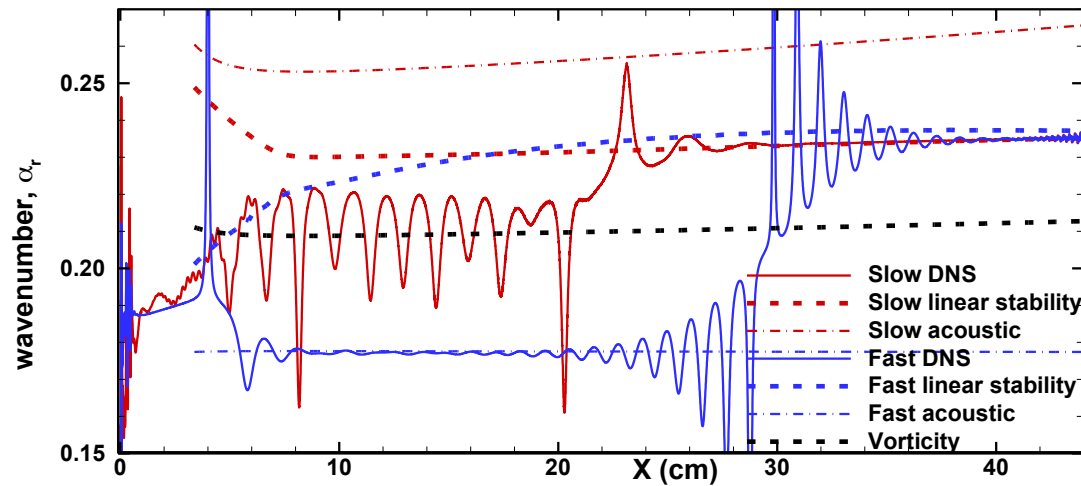
(b) Fast



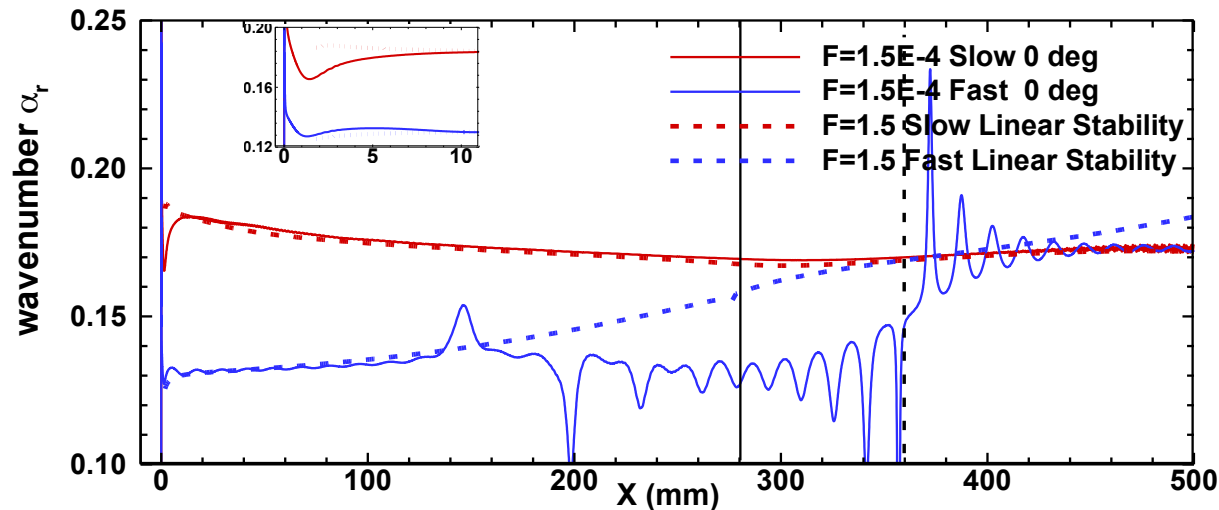
$$C_{recpt, p_{wall}} = \frac{(p_{wall})_n}{p_{ac}} = 10 * 10^{-3} \quad (x \sim 10cm)$$

$$\frac{p_{wall}}{p_\infty} = 0.0055 \quad (x \sim 40cm)$$

# DNS (Flared-Blunt-Cone)

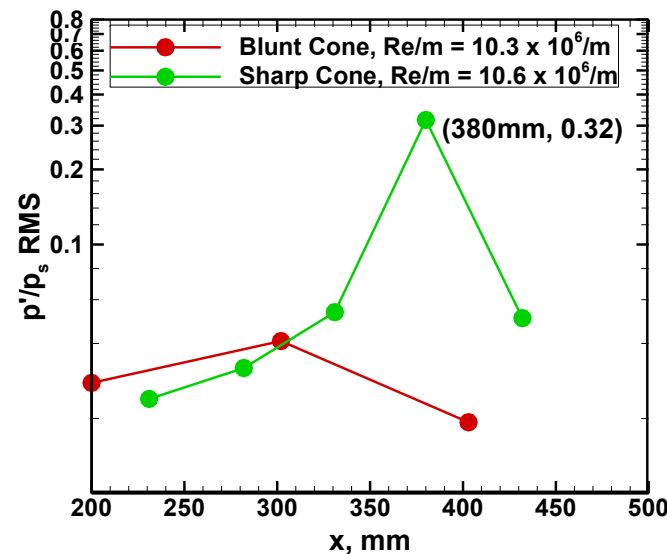
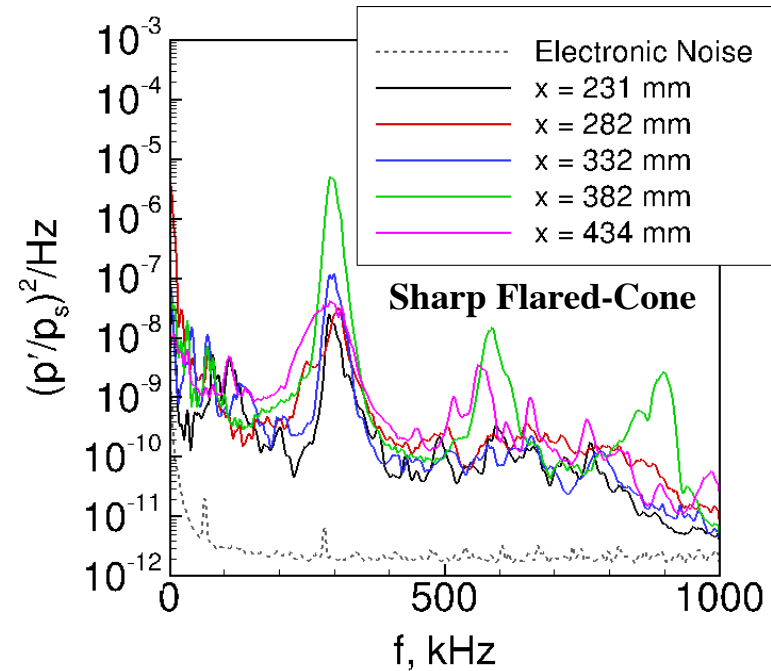
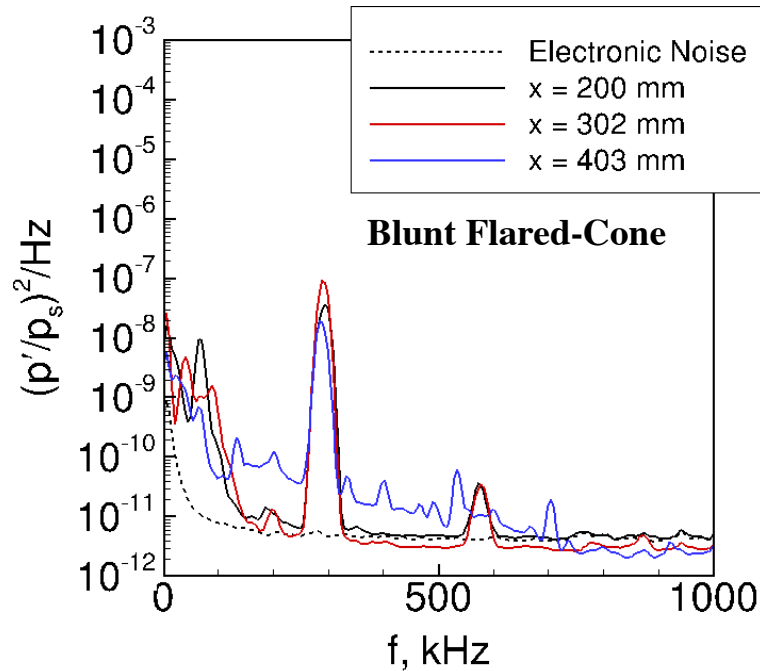


**$X \sim 22$  cm (Slow)**  
 **$X \sim 30$  cm (Fast)**



**Straight sharp cone**

# Expts. (Flared-Sharp and Blunt-Cones)



Amanda et al. AIAA-2015-1734

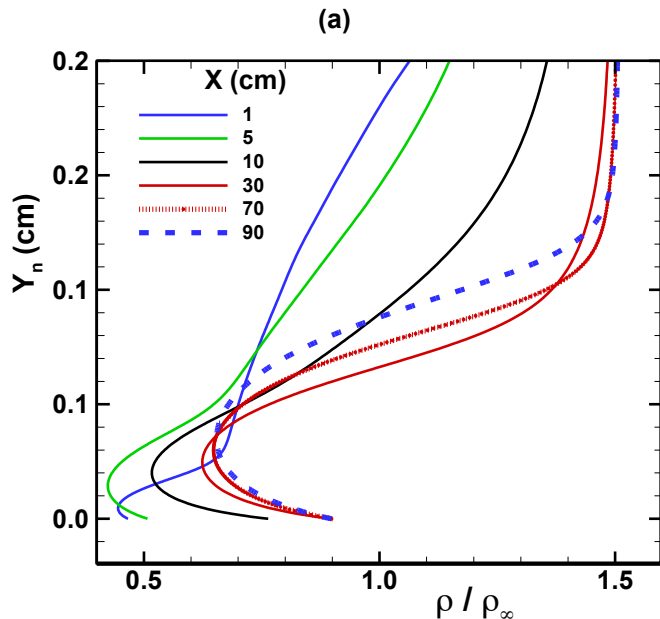
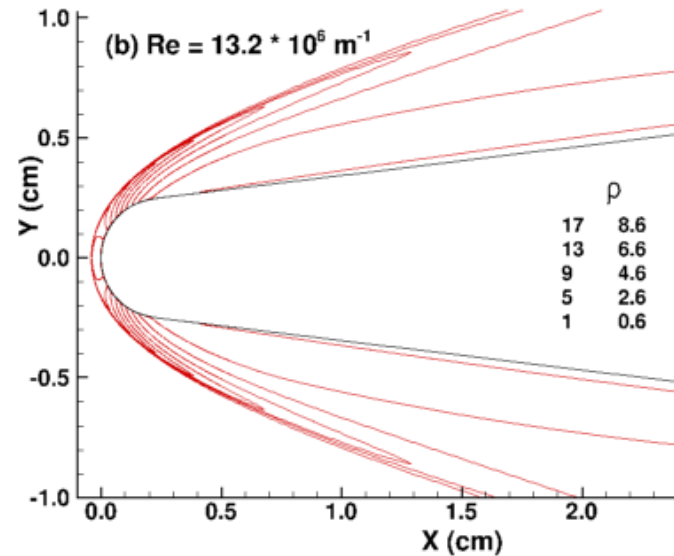
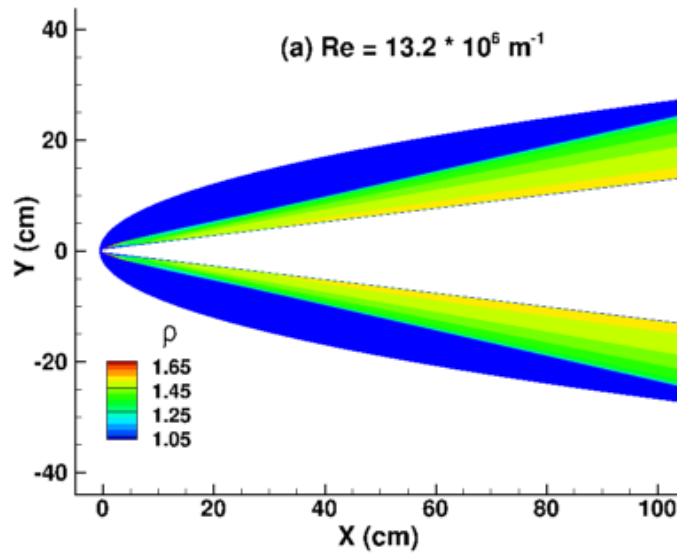




## **Conclusions**

- A small bluntness affected the receptivity process over flared cones. Compared to the sharp flared-cone case, the receptivity coefficient is about 200 times smaller for the blunt flared-cone.
- These conclusions agree with the experimental data.

# HIFiRE-1 (Kimmel et al. 2010) (t=21.5 sec)



T = 21.5 sec

Cone half-angle = 7 deg.

Nose radius = 2.5 mm ( $Re_n=33000$ )

Mach number = 5.3

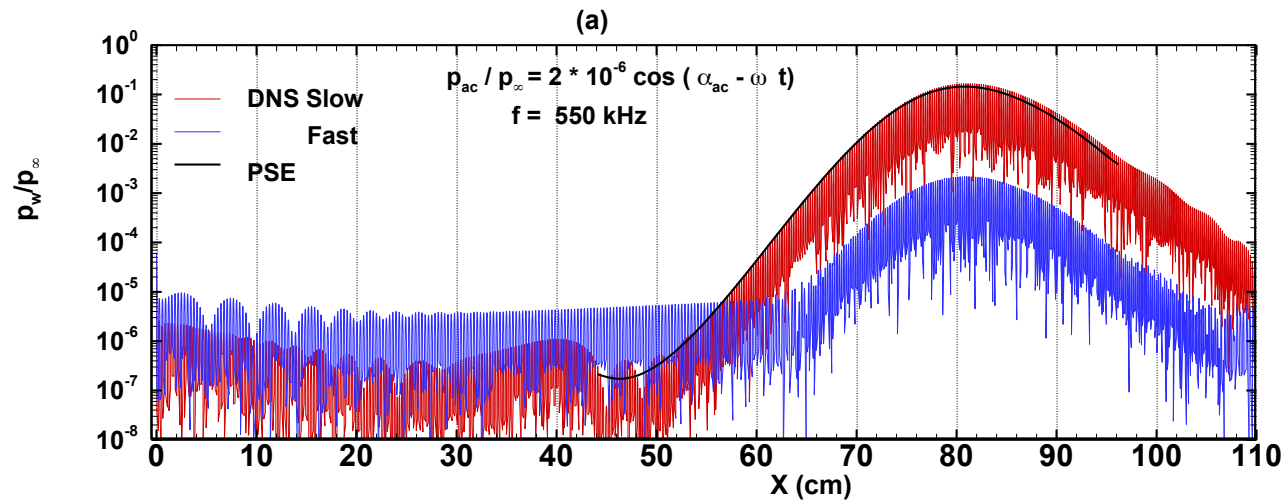
Freestream temp. = 201.4 K

Reynolds number =  $13.2 \cdot 10^6/\text{m}$

Transition onset = 0.805 m

Angle of attack = 0.0 deg

# DNS (HIFiRE-1)



$$C_{recept, p_{wall}} = \frac{(p_{wall})_n}{p_{ac}}$$

$$= 1 * 10^{-1} \quad (x \sim 47 \text{ cm})$$

$$\frac{p_{wall}}{p_\infty} = 2.0 * 10^{-7} \quad (x \sim 47 \text{ cm})$$

$$\frac{(p_{wall})_{\max}}{p_\infty} = 0.17 \quad (x \sim 80 \text{ cm})$$

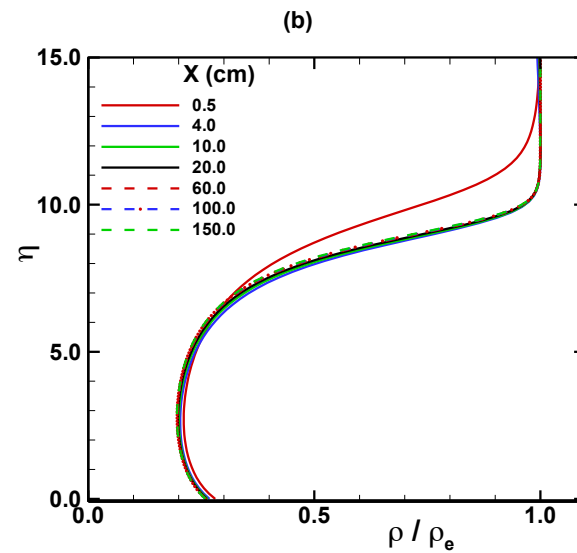
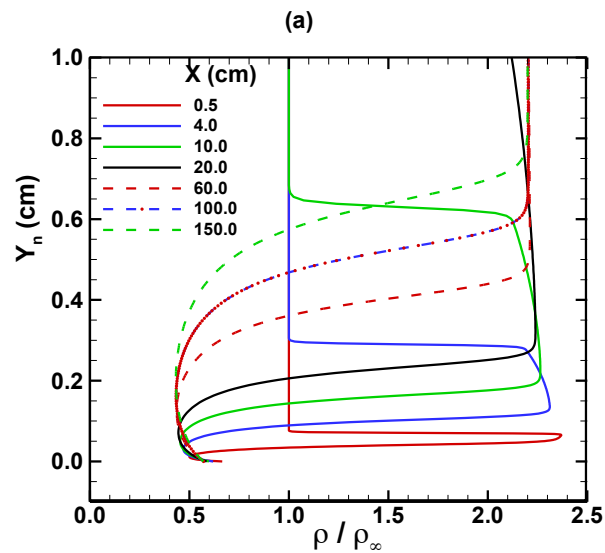
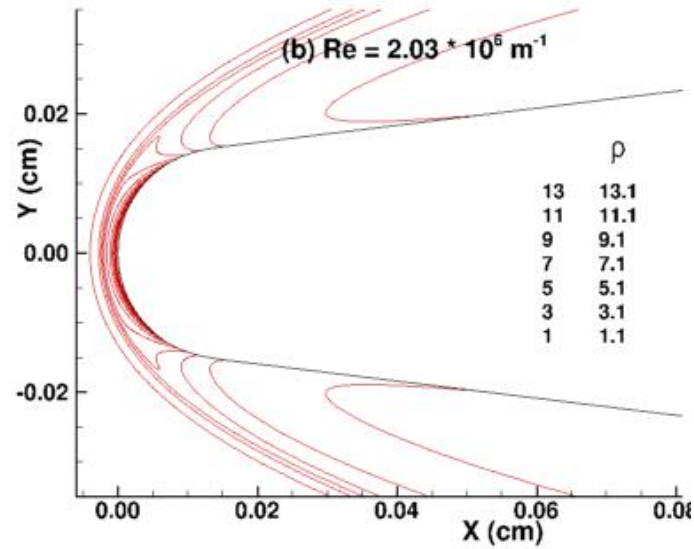
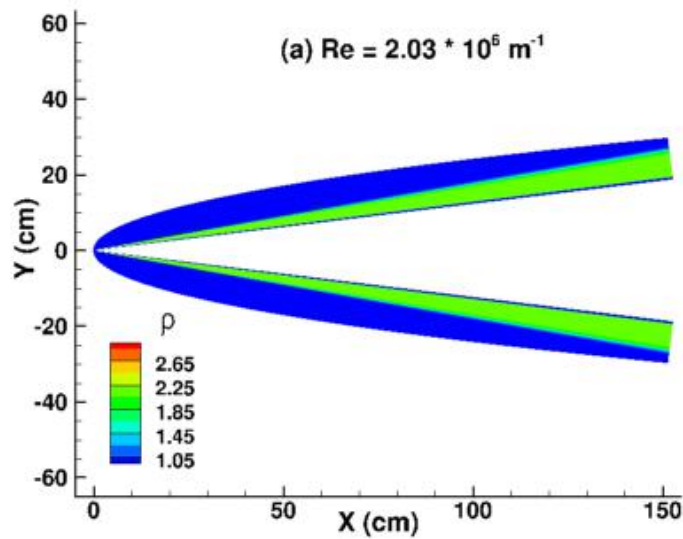
$$N - \text{Factor} = 13.8$$



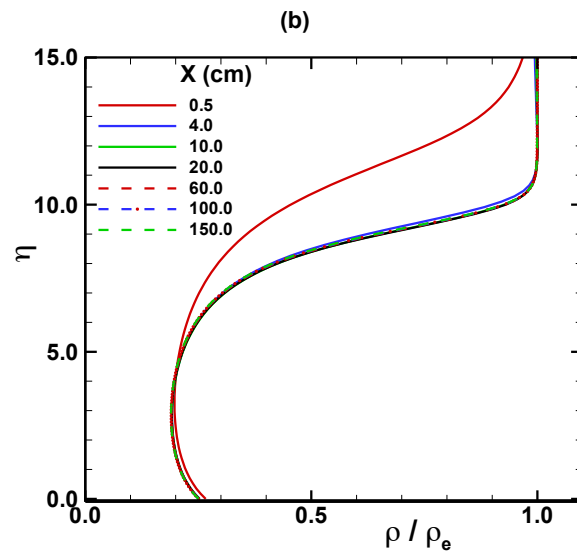
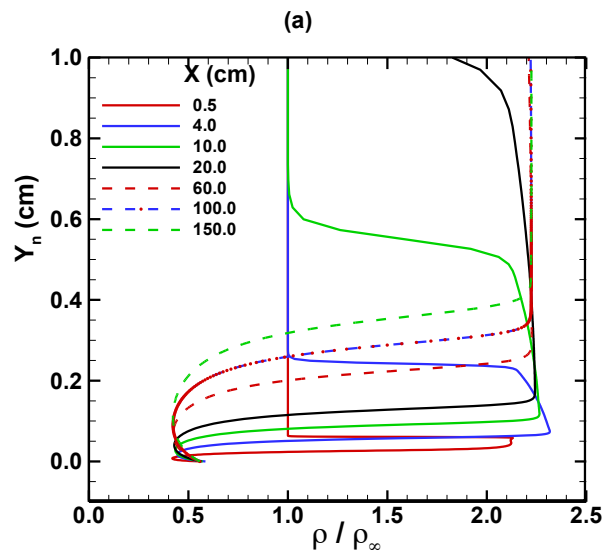
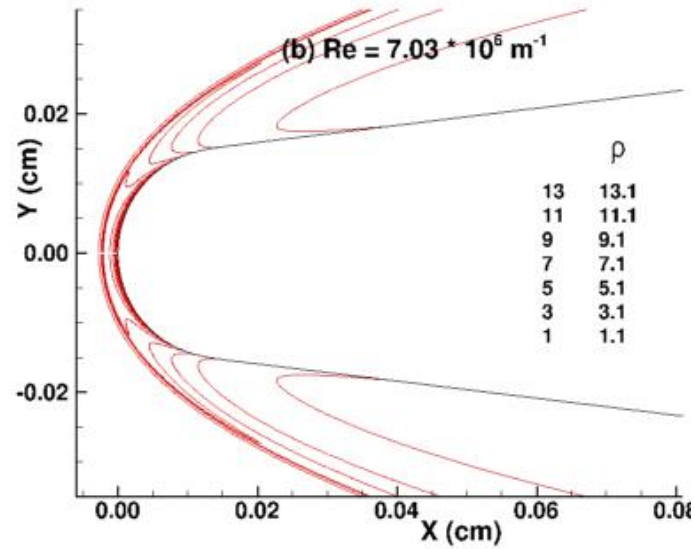
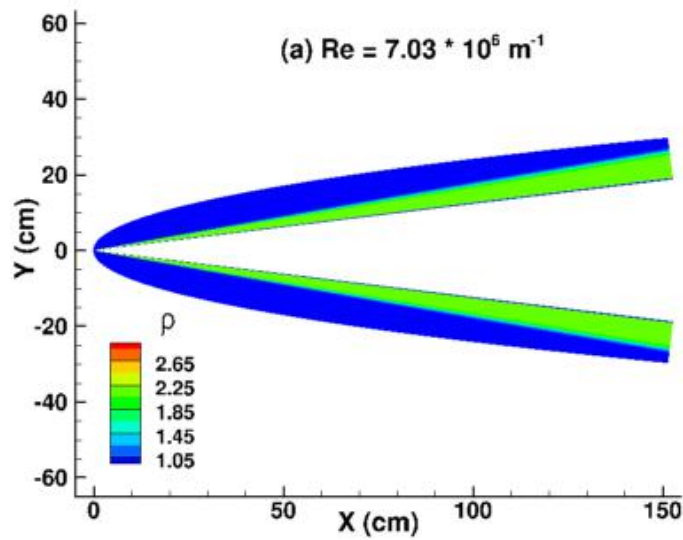
## Conclusions

- Cooling and bluntness stabilized the first mode. The disturbances started to grow from  $x \sim 50$  cm.
- Maximum amplitude reached with the free stream acoustic level of  $(1. \cdot 10^{-6})$  is 0.17. At the transition onset it should be  $\sim 1.4$ .

# Mean Flow (Case 1)



# Mean Flow (Case 2)



# DNS

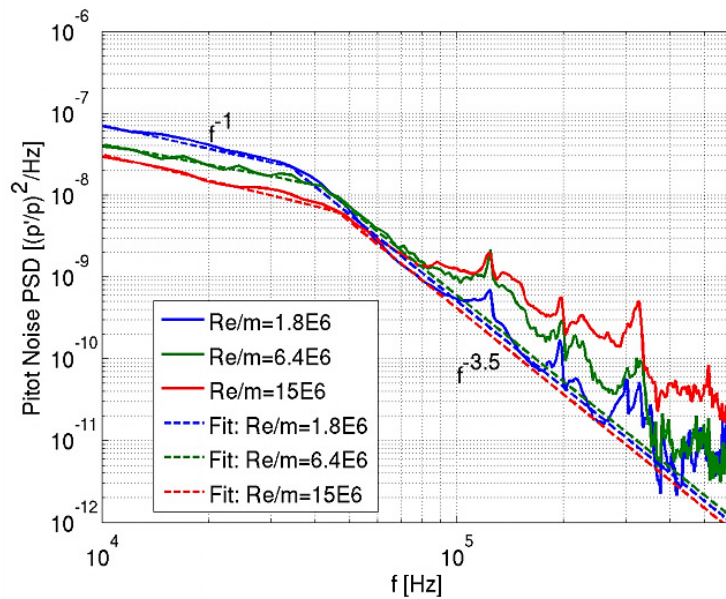


Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)

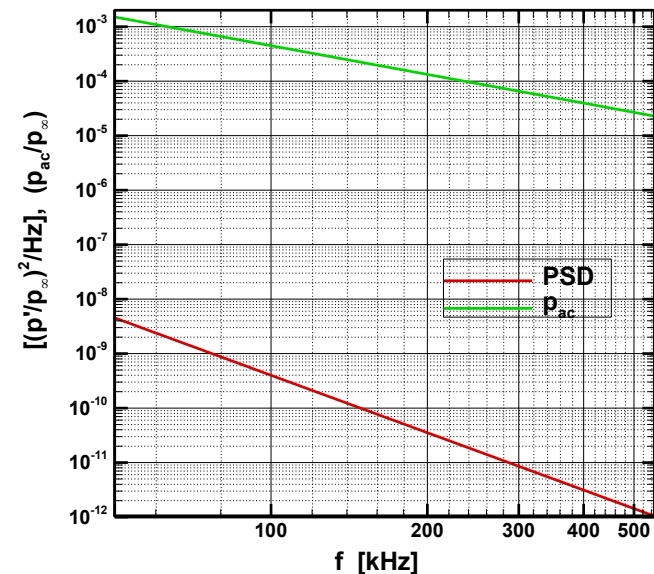
$$p_{ac}(x, t) = \tilde{p}_{ac} e^{i(\alpha_{ac}x - \omega t)} + c.c.,$$

$$(p_{ac})_{PSD} = 2 \left( \tilde{p}_{ac} \right)^2$$

Measured spectrum  $(p_{ac})_{PSD} = C f^{-3.5} / \text{Hz}$

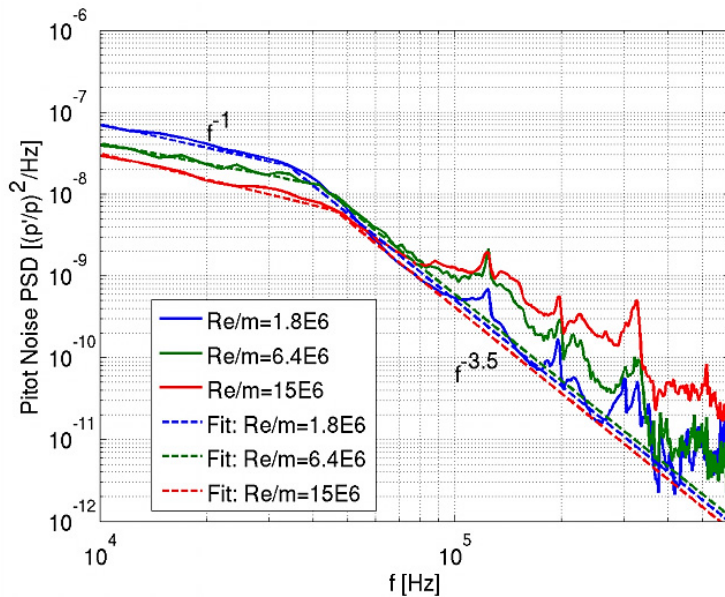
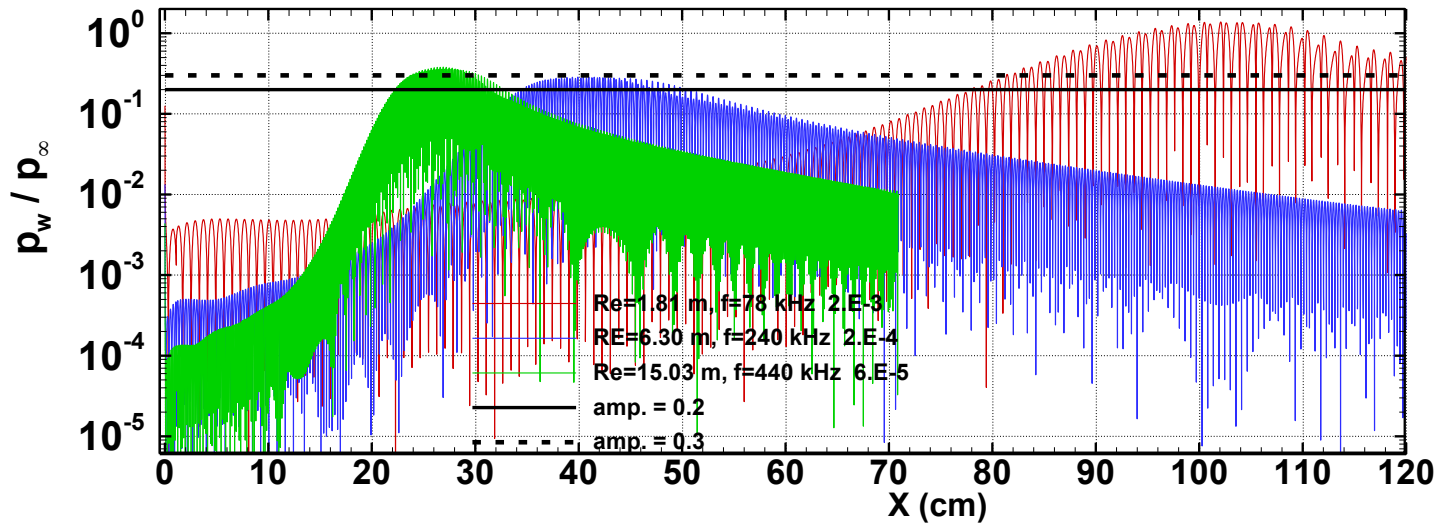
$$2 \left( \tilde{p}_{ac} \right)^2 = C f^{-3.5} \Delta f$$

$\Delta f \sim 10$  to  $100 \text{ kHz}$  (need to investigate more)



# DNS

Cases 1-3



$$p_{ac}(x, t) = \tilde{p}_{ac} e^{i(\alpha_{ac}x - \omega t)} + c.c.,$$

$$(p_{ac})_{PSD} = 2 \left( \tilde{p}_{ac} \right)^2$$

Measured spectrum  $(p_{ac})_{PSD} = C f^{-3.5} / \text{Hz}$

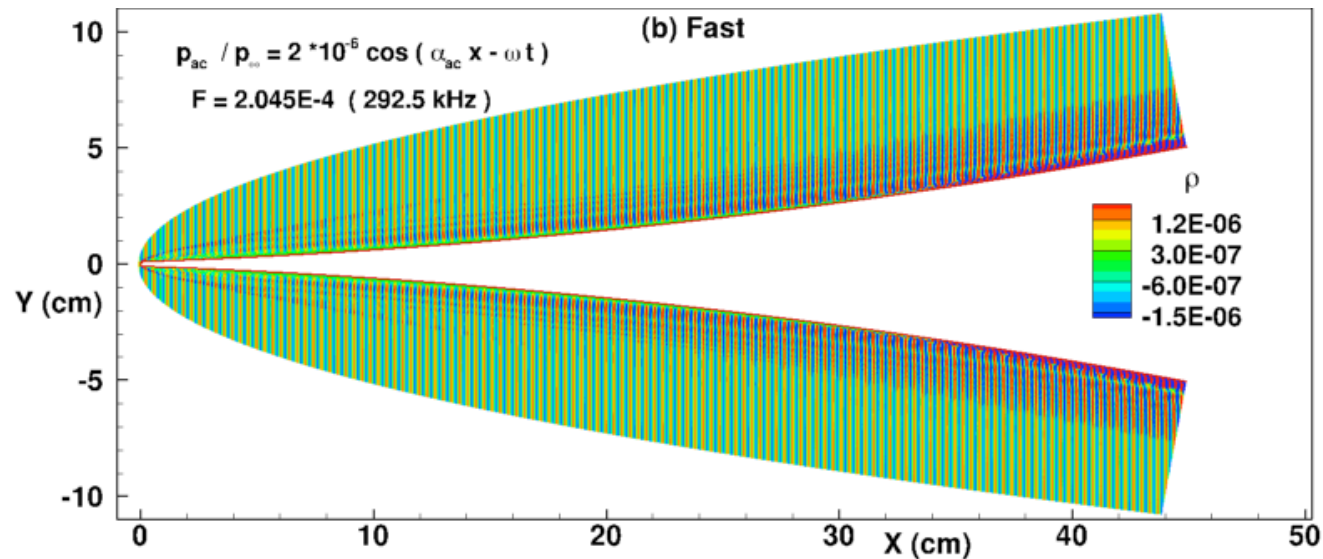
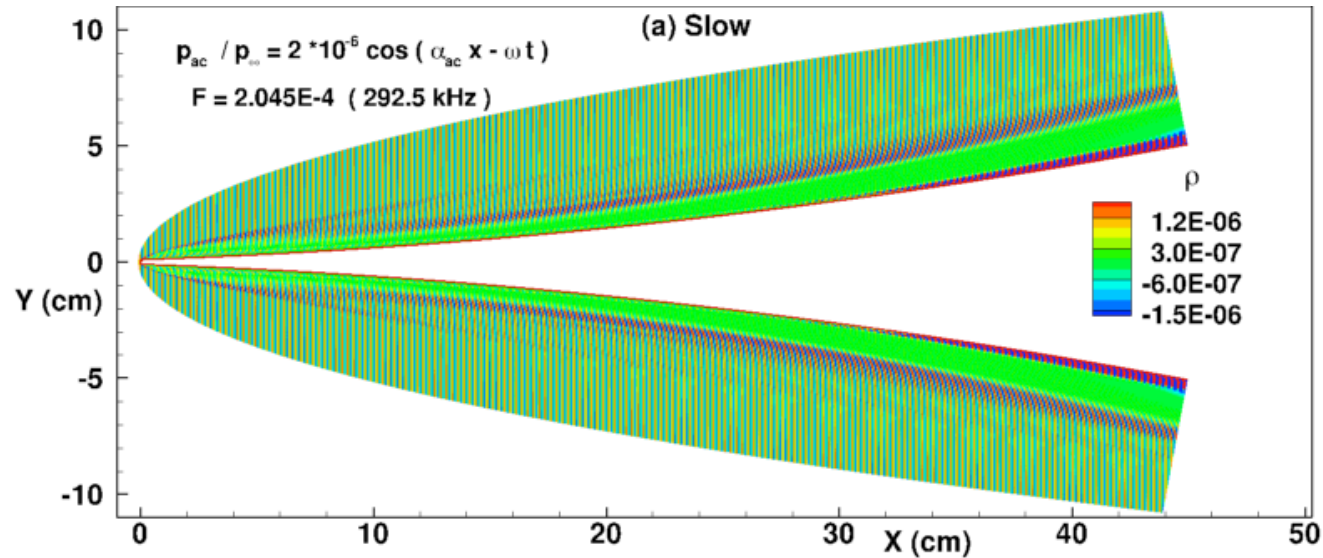
$$2 \left( \tilde{p}_{ac} \right)^2 = C f^{-3.5} \Delta f$$

$\Delta f \sim 10 \text{ to } 100 \text{ kHz}$  (need to investigate more)

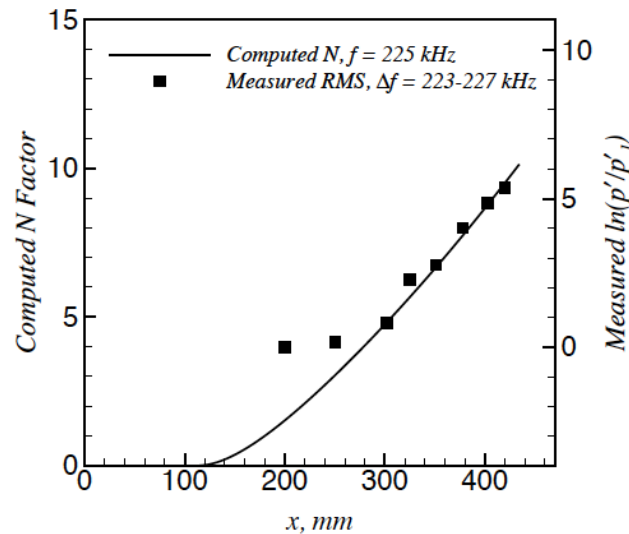
Fig. 18 PSD from expt. (Marineu et al. AIAA 2015)



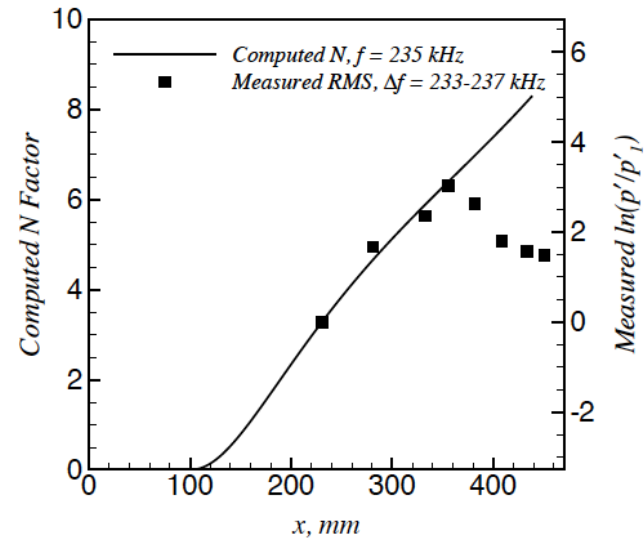
# DNS (Flared-Blunt-Cone)



# Expts. (Flared-Blunt and –Sharp Cones)



(a)  $r_n = 1$  mm. Computation:  $p_0 = 600$  kPa,  $T_0 = 411$  K,  
 $\rho_\infty = 0.026$  kg/m<sup>3</sup>. Experiment:  $p_0 = 605.5$  kPa,  
 $T_0 = 412.3$  K,  $\rho_\infty = 0.026$  kg/m<sup>3</sup>.



(b)  $r_n = 0.16$  mm. Computation:  $p_0 = 535$  kPa,  
 $T_0 = 428$  K,  $\rho_\infty = 0.023$  kg/m<sup>3</sup>. Experiment:  
 $p_0 = 537.6$  kPa,  $T_0 = 429.0$  K,  $\rho_\infty = 0.023$  kg/m<sup>3</sup>.

# DNS (HIFiRE-1)

